

V1647 Ori (IRAS 05436–0007) in Outburst: the First Three Months

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Received _____; accepted _____

ABSTRACT

We report on photometric (BVRIJHK) and low dispersion spectroscopic observations of V1647 Ori, the star that drives McNeil’s Nebula, between 10 February and 7 May 2004. The star is photometrically variable atop a general decline in brightness of about 0.3-0.4 magnitudes during these 87 days. The spectra are featureless, aside from $H\alpha$ and the Ca II infrared triplet in emission, and a Na I D absorption feature. The Ca II triplet line ratios are typical of young stellar objects. The $H\alpha$ equivalent width may be modulated on a period of about 60 days. The post-outburst extinction appears to be less than 7 mag. The data are suggestive of an FU Orionis-like event, but further monitoring will be needed to definitively characterize the outburst.

Subject headings: stars: individual (V1647 Ori, IRAS 05436-0007) — stars: pre-main sequence

1. Introduction

The appearance of a new star is a noteworthy event. Since the discovery of a newly visible nebulosity in the L1630 dark cloud (McNeil 2004), the eruptive object that illuminates McNeil’s nebula has generated a flurry of interest (Reipurth & Aspin 2004; Ábrahám et al. 2004; Briceño et al. 2004; Vacca, Cushing, & Simon 2004; Andrews, Rothberg, & Simon 2004). Such outbursts of young stars are believed to arise from enhanced accretion events from a circumstellar accretion disk. Two classes of eruptive young stellar objects have been previously identified (Herbig 1977): the FU Orionis objects (FUors) and the EX Lupi-like EXors. McNeil’s nebula itself is variable, and visible presumably only while the illuminating object is in outburst. We report here on three months of optical spectroscopic and optical and near-IR photometric monitoring beginning immediately following the report of the discovery. The long term variations we see may help clarify the nature of the eruptive object.

The eruptive object, V1647 Ori, is positionally coincident with the IR source IRAS 05436–0007, the sub-mm source OriB55smm (Mitchell et al. 2001), the mm source LMZ 12 (Lis, Menten, & Zylka 1999), and the near-IR point source 2MASS J05461313–000648. Lis et al. (1999) proposed that the pre-outburst source was an embedded Class 0 object, with a bolometric luminosity of about $2.7 L_{\odot}$. Ábrahám et al. (2004) contrasted the quiescent state of the object with the observed properties of both the FUor and EXor classes. Based primarily on spectral energy distributions (SEDs) they concluded the object resembled more the FU Orionis objects, because the flat-spectrum indicates the presence of a circumstellar envelope. They inferred a bolometric luminosity of $5.6 L_{\odot}$; the larger luminosity is attributable to a more complete SED than used by Lis et al., including additional 2MASS and ISO data. Their resulting SED is that of a Class I/II source with a fairly massive circumstellar envelope. Andrews et al. (2004) concur, but by ascribing different dust

properties they find the envelope to be less massive, and a bolometric luminosity of $3.4 L_{\odot}$. Nevertheless, the disk mass derived in both cases is significantly higher than found for most Class II disks. Either way, the luminosity suggests that V1647 Ori is a low mass object.

Briceño et al. (2004) show that the current outburst began between 28 October and 15 November 2003. They detected the object on three occasions in 1999 with I_c between 18.4 and 20.3. Eislöffel & Mundt (1997) noted the object on a deep I-band image obtained in 1995. The 2MASS JHK detections occurred in October 1999 (Reipurth & Aspin 2004). The nebula itself appeared on an image taken in 1966 (Mallas & Kreimer 1978), which suggests that the star was in outburst at that time.

Published spectra of the object show emission in the hydrogen lines ($H\alpha$, $Pa\beta$, $Pa\gamma$, $Br\alpha$, $Pf\gamma$). $H\alpha$ (Reipurth & Aspin 2004) and the Paschen lines (Vacca et al. 2004) show P Cygni profiles indicative of a strong outflow, with velocities up to 600 km/s. While classical T Tauri stars often show evidence for outflows in $H\alpha$, the velocities are generally smaller and the absorption is seen on a much broader emission line rather than against the continuum. Also in emission are the 2.3-2.5 μ m CO bands and various metallic lines in the K band (Vacca et al. 2004).

Briceño et al. (2004) showed that the spectrum in the direction of HH 22 resembled that of an early B star in February 2004. The Herbig-Haro object HH 22 (Herbig 1974; Eislöffel & Mundt 1997) lies in the direction of the outflow channel illuminated by V1647 Ori. The HH object itself has an emission line spectrum; the continuum is likely reflected off nearby dust. If the HH 22 region is illuminated by V1647 Ori, the continuum would be the reflection spectrum of the star in outburst. However, the observations by Eislöffel & Mundt (1997) appear to indicate that HH 22 was ejected by an as yet unidentified source to its East, as a jet structure is evident in that direction. It may be premature to conclude that V1647 Ori illuminates HH 22; the spectrum of HH 22 could be a composite of sources

contributing to its illumination. Nonetheless, for A_I assumed to be 7.2 mag, the early B spectrum suggests an outburst luminosity of about $220 L_{\odot}$. Vacca et al. (2004) estimated $A_V \sim 11$ mag, based on the optical depth of the $3.0\mu\text{m}$ ice absorption feature using a relation between the $3\mu\text{m}$ optical depth and A_V (Whittet et al. 1988).

Andrews et al. (2004) show that the post-outburst SED, like the pre-outburst SED, is that of a flat spectrum source. They conclude that the post-outburst luminosity lies between 34 and $90 L_{\odot}$. This is less than Briceño’s luminosity estimate primarily because they used a smaller extinction.

What is clear is that V1647 Ori is an eruptive object that is illuminating McNeil’s nebula; what is not clear is the nature of the outburst and the underlying central source. The two primary classes of erupting low mass pre-main sequence stars, the FU Orionis objects and the EXors, are both driven by accretion. The FU Ori objects appear to be the consequence of large-scale instabilities in the inner disk which result in lengthy (decades to centuries long) outbursts, during which time the accretion luminosity of the inner disk dominates (Hartmann & Kenyon 1996). EXors (e.g., Herbig et al. 2001) are classical T Tauri stars that undergo large outbursts (>3 magnitudes) on timescales of weeks to months. Briceño et al. (2004) state that the reflection spectrum resembles those of the FU Orionis object V1057 Cyg shortly after outburst. However, Reipurth & Aspin (2004) note that the near-IR spectra bear some similarity with those of EXors in outburst. Our catalog of eruptive pre-main sequence stars is still very small, and we do not really know what behavior is typical for these objects. A distinction between these two types of objects may be found in the long-term spectrophotometric variations, which have not been addressed to date. That is the aim of this work.

2. Data Reduction and Analysis

All the data we report here were obtained with the SMARTS¹ facilities at Cerro Tololo. All data were obtained by the SMARTS service observers. All dates below refer to the civil date at the start of the night.

We obtained images of the McNeil Nebula field on 25 nights between 10 February and 7 May 2004 (Table 1). With one exception, the images were obtained with the 1.3m ANDICAM imager, which obtains simultaneous optical and near-IR images. We have useful near-IR images on 23 nights. On one night clouds prevented detection of the comparison star, and we have no near-IR data simultaneous with the 0.9m images. We obtained U band images on the first 3 nights, but V1647 Ori is not visible in these images. Exposure times with ANDICAM are 300 sec (B), 109 sec (V, R, I), 160 sec (J), 48 sec (H), and 24 sec (K). The J, H, and K images are dithered, with a 30'' throw to 6 or 7 positions.

The optical ANDICAM data are processed (overscan subtraction and flat-fielding) prior to distribution. Because we obtained only single images through each filter each night, the noise is dominated, in some cases, by cosmic rays and hot pixels. Aside from a 2x2 rebinning, the IR data are delivered raw. We generate the flat field images from the dome flats obtained about every other night. We generate a sky image by taking the median of the dithered images. We subtract the sky image from the individual frames, then shift and add the individual frames.

Standard practice is to use the ANDICAM for differential photometry, but the SMARTS project routinely obtains images of optical and near-IR standard fields on

¹SMARTS, the Small and Medium Aperture Research Telescope Facility, is a consortium of universities and research institutions that operate the small telescopes at Cerro Tololo under contract with AURA.

photometric nights to obtain at least a zero-point for the photometry.

We obtained a set of BVRI images with the 0.9m and the 2k CCD imager on 19 February 2004. The night was photometric. We processed the data using standard IRAF techniques. The residuals to the photometric solution are <0.01 mag. The absolute photometry is presented in Table 2.

The spectra (Table 3) were obtained with the RC spectrograph on the 1.5m telescope. This is a slit spectrograph, with a $300''$ long slit oriented E-W. We observed through a $110\mu\text{m}$ ($1.5''$) slit. We obtained three images at each epoch in order to filter cosmic rays. Each set of images is accompanied by a wavelength calibration exposure. We have developed a pipeline, written in IDL, to process the data. We subtract the overscan, and divide by the normalized flat field image. We generate a median image from the three images. We extract the spectrum, both by using an unweighted boxcar extraction and by fitting a Gaussian profile at each wavelength. In the boxcar extraction, the extraction slit width is determined by fitting a Gaussian to the spatial profile, and the background is measured to either side of the source. We observed a spectrophotometric standard, LTT 4364, each night in order to convert the counts spectrum to a flux spectrum. Due to seeing-related slit losses, we do not obtain absolute fluxes, but rather use this to recover the shape of the continuum.

We obtained the astrometric solution by fitting the stars in the USNO A2 catalog visible in the 0.9m images. V1647 Ori is at 05:46:13.166 -00:06:04.64 (J2000), with uncertainties of less than 0.5 arcsec. This is consistent with the coordinates of the IR counterpart, variously known as 2MASS 05461313-0006048, LMZ 12, and IRAS 05436-0007.

2.1. Differential Photometry

The differential photometry is hampered by the small number of comparison stars available within the 6.3' ANDICAM field of view. Of the three stars visible in the optical channel, two are known T Tauri stars (LkH α 301 [Cohen & Kuhi 1979], and star V of Briceño et al. 2004). We confirm that both are photometrically variable. The other star (J2000 coordinates = 05:46:22.426 -00:03:38.39) appears to be steady to within 0.05 mag, based on comparisons with photometric standards on photometric nights. The BVRI magnitudes of this star, from the photometrically-calibrated 0.9m image, are listed in Table 2.

Because of possible contamination by the variable nebula, it is important to understand the near-star environment and the nebular contribution to the background. To minimize contamination by the nebula, we use a 1.85'' (5 pixel) radius aperture to extract the source counts from the optical images. The background is the median within an annulus with inner and outer radii of 10 and 20 pixels, respectively. Any nebular emission within the annulus is rejected by taking the median, since the nebula occupies a small fraction of the annular area. We verified that we are not oversubtracting the background by examining the data within the annulus. The adopted background level matches the observations to the south and east of V1647 Ori; to the northwest diffuse emission from McNeil's Nebula dominates.

We cannot be confident that we are not undersubtracting the sky, since there may well be significant nebular emission within the 1.85'' extraction radius. There is spatially-asymmetric emission within the 1.85 to 3.7'' gap. This is a southward continuation of the extended nebula in towards V1647 Ori. To quantify this, we extracted cuts through the images on a night with good seeing (23 March). These cuts passed through V1647 Ori with a position angle of between 20° and 30°. The surface brightness of McNeil's Nebula peaks about 10'' from V1647 Ori. We extrapolated the surface brightness of the nebula

linearly from about $5''$ north-northeast of the star in order to estimate the degree of contamination of the starlight by background nebulosity. Under this assumption we find that the maximum contribution of the nebula within the inner $1.5''$ is 7% of the total flux in the I band, 11% at R, 23% at V, and 13% at B. The relatively large contamination at V is due to the fading of the source; the relatively smaller contribution at B is due to the fading of the nebulosity.

In the smaller ($2.4'$ square) IR channel, there is only one other star visible, at 05:46:11.68 -0:06:28.3 (J2000). This is 2MASS 05461162-0006279 ($J = 13.94$, $H = 12.19$, $K = 11.20$), and by default it is our comparison star. We know nothing else about this star. We used a $2.5''$ (9 pixel) radius extraction aperture for the photometry. The mean IR magnitudes of our target are $J = 10.9$, $H = 8.9$, $K = 7.3$, in good agreement with the near-IR magnitudes reported by Reipurth & Aspin (2004).

The differential light curves are shown in Figures 1 and 2. In both the optical and near-IR there is a general downwards trend. The trend is significant at $>99.8\%$ confidence in all bands except B , where the star is faintest and contamination from the nebula is greatest. Over the 87 days we followed the star, the mean brightness decreased by about 0.4 mag at I and 0.3 mag at K . We detect no significant color changes; over this time the mean $V - K$ color reddened by 0.18 ± 0.16 mag.

The general downward trend is superposed on a variable source. Only about 30% of the RMS scatter is attributable to any long-term trends. There are dips in the optical light curve around 7 March and 12 April. The dips are most pronounced at the shortest wavelengths, and are not visible in the near-IR, suggesting that they may be due to variable dust obscuration with a change in A_V of 0.2-0.3 mag.

In Table 1 we record the measured FWHM of the stellar PSF in the I band. This is determined from a Gaussian fit to two stars, LkH α 301 and star V, and is a measure

of the seeing averaged over the 109 second integrations. We see no correlations between the relative brightnesses and the seeing, which suggests that the brightness variations are intrinsic to V1647 Ori (or an unresolved compact nebula).

We repeated the aperture photometry with a smaller 3 pixel ($1.1''$) radius aperture. The shape of the light curve is identical, within the errors, to that extracted with the larger aperture. This is further evidence that the source of the variations is not McNeil’s Nebula, but is V1647 Ori, or perhaps a very compact nebula within $1''$ of the star. The principal effect of any nebular contamination will be to dilute the amplitude of any stellar variations, and to affect the inferred colors at short wavelengths.

2.2. Spectroscopy

We obtained spectra on 10 nights between 13 February and 17 April 2004 (Table 3). Eight are first order spectra using grating 47 and the GG 495 order sorting filter to obtain 3.1\AA resolution between 5650 and 6970\AA . This resolution is sufficient to resolve the $\text{H}\alpha$ line. Two spectra were obtained using grating 13 unfiltered, which yields a 17.2\AA resolution spectrum over nearly the full optical spectral region from 3150 to 9370\AA .

The spectra show few features. $\text{H}\alpha$ is in emission (Figure 3), with a P Cygni absorption feature, as reported by Reipurth & Aspin (2004). Our resolving power is about 40% of theirs, so we are not sensitive to any structure in the outflow profile.

The equivalent width of the $\text{H}\alpha$ emission line varies from -30\AA to -48\AA (see Table 4), with formal measurement uncertainties of order 0.1\AA . Systematic uncertainties in the placement of the weak continuum dominate the uncertainties. Many of the spectra were taken before the end of twilight, with the sky brightness comparable to that of the star. We estimate that the systematic errors in the equivalent width are about $\pm 1\text{\AA}$. The -32\AA

equivalent width reported by Reipurth & Aspin (2004) on 14 February is identical to the equivalent width we observed the previous night. The equivalent width of the emission line varies at the $\pm 20\%$ level. The time variation (Figure 4) is suggestive of an oscillatory or periodic variation, but we sample too short a time interval to permit us to draw any conclusions.

We note that there appears to be an anticorrelation between the equivalent widths of the P Cygni absorption feature and of the $H\alpha$ emission line. A modulation of the wind velocity or optical depth could yield this sort of anticorrelation. However, our spectral resolution is insufficient to permit any meaningful line profile fitting.

We do not see any emission at $H\beta$. We can trace the continuum down to about 4300\AA . The limiting equivalent width, based on the noise in the 4860\AA continuum, is about 5\AA .

The Na I D lines are seen in absorption, apparently saturated, with an equivalent width of 14\AA . This is consistent with the large extinction seen towards the star.

The Ca II IR triplet is in emission (Table 5, Figure 5). The star shows the unique $\approx 2:2:1$ pattern seen only in T Tauri stars and Herbig Ae/Be stars (Hamann & Persson 1992a, b). These line ratios are inconsistent with the $1:9:5$ gf values, and are inconsistent with either pure optical depth effects or simple chromospheric models (Hamann & Persson 1992a). The presence of the Ca IR triplet lines in this emission pattern confirm that the star is a pre-main sequence star, but we cannot use the fluxes to determine whether the underlying star is a low mass classical T Tauri star or a more massive Herbig Ae star.

3. Discussion

The discovery of a new star was once considered a portent, often with dire consequences. In today’s more rational cosmology, a new star offers an opportunity to probe some of the

earliest and best hidden processes of the building of stars. It has been suggested that rapid disk accretion via the FU Orionis episodes is a major source of the mass that builds low mass stars, since the inferred mass accreted in these events is comparable to that accreted at a lower rate over the 10^6 year pre-main sequence phase of a classical T Tauri star (see review by Hartmann & Kenyon 1996). As our characterizations of these episodes, and our inferences concerning outburst timescales and recurrence rates, are based on a small and inhomogeneous sample (5–9 stars as of the Hartmann & Kenyon review), every new outbursting pre-main sequence star can contribute a great deal to our understanding of these phenomena.

The pre-outburst star had a luminosity between 2.7 and 5.6 L_{\odot} , which is typical of a low mass classical T Tauri star (Lis et al. 1999, Ábrahám et al. 2004, and Andrews et al. 2004). This is based on integrating the $1\mu\text{m}$ - 1.3mm spectrum. The small discrepancy in the luminosity is the consequence of the different choices of A_V , and inclusion of slightly different data sets.

If V1647 Ori is an FU Orionis object, then the reflection spectrum from the vicinity of HH 22 would mirror the inner edge of the accretion disk. An A-type spectrum with $T_{eff} \sim 8000\text{K}$, as seen in V1057 Cyg shortly after outburst, is consistent with this scenario. This temperature, and the $\sim 50 L_{\odot}$ luminosity (Andrews et al. 2004), suggests an inner disk radius $R_i = 3.7 [(L/50 L_{\odot})/(T/8000 \text{ K})^2]^{-\frac{1}{2}} R_{\odot}$, and a mass accretion rate $\dot{M} = 3 \times 10^{-5} \frac{L}{50 L_{\odot}} \frac{R_i}{3.7 R_{\odot}} \frac{0.5 M_{\odot}}{M} M_{\odot}/\text{yr}$. For the range of luminosities and temperatures being considered, these mass accretion rates and inner disk radii are consistent with, though typically lower than, those of known FUors (Hartmann & Kenyon 1996).

3.1. Limits on the Spectral Type of V1647 Ori

With a luminosity of only a few L_{\odot} before the outburst, V1647 Ori was likely of spectral type K–M, although the optical and near-IR spectrum may have been heavily veiled by quiescent accretion. Briceño et al. (2004) make the case that the reflection spectrum in the vicinity of HH 22, which resembles that of an early B star or A star, is the spectrum of V1647 Ori in outburst, seen via a clear channel through the surrounding dust. The hot blue photosphere could be that of a Herbig Ae star (unlikely, given the pre-outburst luminosity) or the luminous, optically thick inner part of the accretion disk. We have examined our spectra in hopes of obtaining some clarification.

As mentioned earlier, the spectra are featureless, with the exception of $H\alpha$ and the Ca IR triplet in absorption, and the Na I D lines in absorption. We see no evidence of TiO absorption bands, which means that, in the absence of overwhelming veiling, the spectral type of the photosphere can be no later than K7. The limiting equivalent width of narrow absorption lines in our coadded spectrum (Figure 4) is 0.7\AA . We would not expect to detect narrow lines from any star hotter than about spectral type K0, since the lines in the red are weak in the F-G stars. In the presence of significant veiling, we can say even less.

If the spectrum is that of an A-F supergiant (the low density photosphere of the hot disk), as was V1057 Cyg, the O I $\lambda 7774\text{\AA}$ triplet should be prominent in absorption. There is a possible absorption line here ($W_{\lambda}=2.6\text{\AA}$), but it is near the noise level in the coadded low resolution spectrum and, absent further information, is not significant.

The observed B through K colors of the star in outburst are more consistent with a heavily reddened hot star than with a cool star. We unreddened the observed colors of V1647 Ori using the parameterizations of Cardelli, Clayton, & Mathis (1989). R , the ratio of total to selective extinction, was a selectable parameter. We then compared the unreddened colors to template stars AB Aur, a Herbig Ae star, and T Tau, the prototypical

low mass pre-main sequence star. The observed B through K colors are somewhat consistent with the observed colors of the Herbig Ae star AB Aur, for $R \sim 5$ and $A_V \sim 7-8$ mag. A star with the colors of T Tauri requires a much smaller A_V of ~ 4 mag. This is not to say that V1647 Ori is a hot star; rather it is consistent with the post-outburst light being dominated by a hot photosphere, perhaps an inner accretion disk, as in the case of the FU Orionis objects.

3.2. The Extinction Towards V1647 Ori

Estimates of the extinction towards V1647 Ori are highly uncertain, because the shape of the underlying spectrum is unknown, and because there is no constraint on R , the ratio of total to selective extinction. While we have no *a priori* information on the value of R , we favor a large value of R . $R \sim 5$, indicative of large grain sizes, is commonly found for embedded objects, and in regions of star formation (e.g., Savage & Mathis 1979; Cardelli & Clayton 1988), where large grains may contribute to significant gray extinction.

Ábrahám et al. (2004) dereddened the pre-outburst star on the $J-H$, $H-K$ color-color diagram, apparently using $R=3.1$, until it lay on the unreddened classical T Tauri star locus. They concluded that $A_V=13$ mag. Had they dereddened the star using $R=5.5$, they would have estimated A_V to be about 2 magnitudes less.

Vacca et al. (2004) used the empirical relation between $\tau(3.1\mu\text{m})$ and A_V (Whittet et al. 1988) to estimate $A_V=11$ mag. There is significant scatter around this relation. In particular, the deeply embedded source HL Tau has $\tau(3.1\mu\text{m}) = 0.85$ (larger than V1647 Ori) but A_V of only 6-8 mag. The Whittet et al. (1988) relation was calibrated for stars in the Taurus clouds, and there is evidence that the $\tau-A_V$ relations (and by inference the grain properties) vary between different star formation regions (Teixeira & Emerson

1999).

Briceño et al. (2004) state that the optical continuum slope is consistent with $A_V=8-10$ mag, for an underlying A–B star photosphere.

We use the observed SED in the optical and near-IR to constrain A_V , on the assumption that emission in the optical is thermal, and consists of a single dominant temperature component. For a hot blackbody, we find that $A_V < 9.7$ mag for $R=5$ and $A_V < 6.8$ mag for $R=3.1$. In the more realistic case where the temperature is 8000–10,000K (consistent with a hot inner accretion disk or an A star photosphere), we can place upper bounds on A_V of 6.7 or 4.5 mag for $R=5$ and 3.1, respectively.

Reipurth & Aspin (2004) find that the extinction apparently decreased by 4.5 mag between the pre- and post-outburst apparitions. Following the Ábrahám et al. (2004) approach to de-reddening, the difference between our outburst J–H color and the pre-outburst 2MASS color yields $\Delta(J-H)=3.6$ mag, or a decrease of $A_V \sim 5.4$ mag during outburst. The possibility of reprocessing by scattering to longer wavelengths makes this a minimum estimate. These two determinations are consistent in indicating that the extinction decreased significantly during outburst, with A_V decreasing from about 11 to about 6 mag. Either a great deal of dust was sublimated during the outburst, or the wind blew a large hole in the circumstellar envelope.

3.3. The SED in the Optical and Near-IR

We can fit the optical and near-IR (B through K) spectral energy distribution as the sum of two blackbody components. Figure 6 shows the case where the hotter blackbody is 8000 K and R is 5.0. A_V and the temperature of the cooler blackbody are fit by eye. Given these assumptions, the fit is unique, but we are able to obtain good fits for any temperature

exceeding 4000 K. The temperature of the cool component always lies between 1200K and 1500K. The inferred extinction, which makes the hot blackbody match the BVRI data, varies from 1.7 mag ($R=3.1$, $T_{BB}=4000\text{K}$) to 9.7 ($R=5.0$, $T_{BB}=100,000\text{K}$). Physically these two components represent the boundary layer or inner accreting material, and the inner part of the dust disk, but don't address cooler material further from the star.

These two blackbody fits are consistent with the results of matching the spectral energy distributions of AB Aur and T Tau, reported above. The two-blackbody fits lie below the L' and M' fluxes reported by Vacca et al. (2004), as expected for a flat spectrum source.

We can also fit the same data with a hot blackbody and a disk model (with temperature decreasing as $r^{-\frac{3}{4}}$). The extinction is set by matching the hot blackbody to the optical points, and is identical to that of the two-blackbody case. Again, the model is not unique, but we obtain a good fit with an inner dust disk temperature of 1450K and an inner disk radius of $12 R_{\odot}$. This disk model reproduces the L' and M' fluxes. These values for the disk temperature and inner radius are reasonable for a pre-main sequence circumstellar disk.

3.4. FUor or EXor?

Briceño et al. (2004) note that early spectra of the FU Orionis object V1057 Cyg have $H\alpha$ profiles similar to those seen in V1647 Ori, but Reipurth & Aspin (2004) argue that the spectra are unlike those of mature FUors. They suggest that V1647 Ori may be an example of an EXor. While EXors and FUors have comparable outburst amplitudes, the lengths of the outbursts are very different, with FUors staying bright for decades. Over the course of our observations, V1647 Ori has faded by about 0.3–0.4 mag.

V1647 Ori was apparently bright around 1966. This recurrent nature, and the relative rapidity of the fading (about 3-4 times as fast as V1057 Cyg – see Geiseking 1973), are

unlike any known FUor but is more typical of the EXors. V1647 Ori appears to have varied less erratically than did EX Lup during the 87 days following any of its peaks during the 1993-1994 outburst (Herbig et al. 2001). The 1955-1956 outburst of EX Lup took roughly 3 months to rise to maximum light, varied significantly about maximum light for about 3 months, then rapidly declined to its pre-outburst state within a matter of weeks (e.g., Herbig 1977). While the rise time and duration at maximum light mimics that seen for V1647 Ori, the significant variations seen in the EXor at maximum are not replicated.

We thus do not know how to categorize the star, other than to say that it appears to be a young accreting low mass pre-main sequence star in outburst. V1647 Ori has brightened, and at the same time the extinction has decreased. This may be telling us that there is a continuum of behaviors of accreting low mass pre-main sequence stars, many of which we have yet to see.

4. Conclusions

Based on the optical and near-IR photometry, and the optical spectra, the extinction to V1647 Ori appears to be much smaller than claimed elsewhere, with a post outburst A_V about 6.5 mag. We suggest that R is close to 5. To reconcile $\tau(3\mu\text{m})$ with A_V , we suggest that the dust grains are more like those near HL Tau than the “typical” T Tauri star in Taurus.

After only three months of monitoring, it is not clear whether V1647 Ori is best categorized as a FUor or an EXor, or something in-between. We know few members of either class, there is much variance among members of each class, and our view of how they should behave may be severely biased. However, the preponderance of the evidence to date suggests that this outburst is more like an FU Orionis outburst.

Continued monitoring of V1647 Ori and McNeil’s Nebula when it reappears from behind the Sun late this summer may ultimately tell us how best to characterize this outburst. However we finally decide to categorize this event, this new star does portend a better understanding of the nature of accretion-induced outbursts in pre-main sequence stars.

We are grateful for the support of Dean of Arts and Sciences J. Staros, Provost R. McGrath, and Vice President for Research G. Habich, all of Stony Brook University, for providing partial support that enabled Stony Brook’s participation in the SMARTS consortium. We thank the SMARTS service observers, J. Espinoza, D. Gonzalez, A. Miranda, and A. Pasten, for taking the data, and for their dedication to the SMARTS effort. We thank C. Baily, the driving force behind the SMARTS consortium, and R. Winnick, who accommodated our many requests to revise the photometric timelines. We thank Tracy Beck for sharing her insights into the extinction properties of highly embedded objects. Finally we thank Bo Reipurth, the referee, for his very insightful comments.

This research was funded in part by NSF grant AST-0307454 to Stony Brook University.

REFERENCES

- Ábrahám, P., Kóspál, Á., Csizmadia, Sz., Moór, A., Kun, M., & Stringfellow, G. 2004, A&A, 419, L39
- Andrews, S.M., Rothberg, B., & Simon, T. 2004, ApJ, submitted (astro-ph/0406089)
- Briceño, C., et al. 2004, ApJ, 606, L123
- Cardelli, J.A., Clayton, G.C., & Mathis, J.S. 1989, ApJ, 345, 245
- Cardelli, J.A., & Clayton, G.C. 1988, AJ, 95, 516
- Cohen, M. & Kuhi, L.V. 1979, ApJS, 41, 743
- Eislöffel, J. & Mundt, R. 1997, AJ, 114, 280
- Geiseking, F. 1973, IBVS, 806
- Hamann, F & Persson, S.E. 1992a, ApJS, 82, 247
- Hamann, F & Persson, S.E. 1992b, ApJS, 82, 285
- Hartmann, L. & Kenyon, S.J. 1996, ARA&A, 34, 207
- Herbig, G.H., 1974, Draft catalog of Herbig-Haro objects, Lick Obs. Bull. No. 658
- Herbig, G.H., 1977, ApJ, 217, 693
- Herbig, G.H., Aspin, C., Gilmore, A.C., Imhoff, C.L., & Jones, A.F. 2001, PASP, 113, 1547
- Lis, D.C., Menten, K.M., & Zylka, R. 1999, ApJ, 527, 856
- Mallas, J.H. & Kreimer, E. 1978, The Messier Album, (Cambridge: Sky Publ. Corp.)
- McNeil, J.W. 2004, IAU Circular 8284

- Mitchell, G.F., Johnstone, D., Moriatry-Schieven, G., Fich, M., & Tothill, N.F.H. 2001, ApJ, 556, 215
- Reipurth, B., & Aspin, C. 2004, ApJ, 606, L119
- Savage, B.D. & Mathis, J.S. 1979, ARA&A, 17, 73
- Teixeira, T.C. & Emerson, J.P. 1999, A&A, 351, 292
- Vacca, W.D., Cushing, M.C., & Simon, T. 2004, ApJ, 609, L29
- Whittet, D.C.B., Bode, M.F., Longmore, A.J., Adamson, A.J., McFadzean, A.D., Aitken, D.K., & Roche, P.F. 1988, MNRAS, 233, 321

Fig. 1.— The optical light curves in the B, V, R_C , and I_C bands. The differential magnitudes are relative to a single comparison star (see text), which appears constant to within 0.05 mag. Error bars are $\pm 1 \sigma$, based on counting statistics. The uncertainty will be underestimated should the comparison star turn out to be variable. The S/N is low on JD 2453065 because the field was observed through clouds; the high point in the V band should be discounted. Uncertainties in the B band are large because the star is faint and because there may be some contamination from McNeil’s nebula. The dotted lines represent the mean magnitudes. The downward trend in the V , R , and I bands is significant at $\alpha < 0.002$.

Fig. 2.— The near-IR light curves. The magnitudes are relative to comparison star 2MASS 05461162-0006279 (see text). The dotted lines represent the mean magnitudes. The downward trend in the J , H , and K bands is significant at $\alpha < 0.001$.

Fig. 3.— The mean $H\alpha$ profile, at 3.1\AA resolution. This is the normalized sum of 7 spectra obtained between 13 February and 12 April.

Fig. 4.— The time variation of the $H\alpha$ equivalent width. Units are \AA stroms. The formal uncertainties on the equivalent width measurements are about 0.1\AA , but systematic errors in the placement of the continuum are about an order of magnitude larger. While the data are suggestive of an oscillatory or periodic variation, only about 1.5 periods are sampled, and we offer no interpretation of this.

Fig. 5.— The Ca IR triplet, on 17 April (solid) and 21 March (dashed). The continua have been scaled to match. The equivalent widths changed by about 35%, but the $\approx 2:2:1$ pattern remains steady.

Fig. 6.— A simple two-blackbody fit to the optical (BVRI) and near-IR (JHK) magnitudes in February 2004. We have fixed the temperature of the hotter blackbody at 8000 K, appropriate for an early A star photosphere. We set R , the ratio of total to selective extinction,

to 5. A_V and the temperature of the cooler blackbody are free parameters, fit by eye. The lower solid curve is the 8000K blackbody; the dashed curve is the 1450K blackbody. Both are reddened by $A_V=6.7$ mag. The upper solid curve is the sum of the two reddened blackbodies.

Table 1. Photometric Log

Date (UT)	JD	FWHM ^a	conditions	notes
2004 Feb 11	2453046.604	1.7	cirrus	U image obtained
2004 Feb 12	2453047.674	1.8	photometric	U image obtained
2004 Feb 13	2453048.651	1.2	photometric	U image obtained
2004 Feb 14	2453049.685	1.4	photometric	
2004 Feb 20	2453055.590	1.2	clouds	
2004 Feb 21	2453056.533	2.1	photometric	0.9m images, no IR
2004 Feb 23	2453058.619	1.6	patchy clouds	
2004 Feb 26	2453061.564	2.0	photometric	
2004 Mar 01	2453065.573	1.4	clouds	
2004 Mar 02	2453066.604	1.9	photometric	
2004 Mar 05	2453069.580	1.2	photometric	
2004 Mar 08	2453072.524	1.3	photometric	
2004 Mar 12	2453076.543	1.6	photometric	
2004 Mar 17	2453081.580	1.3	photometric	
2004 Mar 23	2453088.492	1.0	photometric	
2004 Mar 30	2453094.502	1.9	poor seeing	
2004 Apr 02	2453097.513	1.6	cirrus	
2004 Apr 04	2453099.507	1.4	patchy clouds	IR images unuseable
2004 Apr 06	2453102.499	1.1	photometric	
2004 Apr 07	2453103.489	1.3	photometric	
2004 Apr 09	2453105.504	1.4	patchy clouds, cirrus	

Table 1—Continued

Date (UT)	JD	FWHM ^a	conditions	notes
2004 Apr 10	2453106.487	2.2	photometric	
2004 Apr 12	2453108.491	1.9	photometric	
2004 Apr 17	2453113.495	1.3	photometric	
2004 May 07	2453133.447	1.5	photometric	

^aMeasured FWHM of LkH α 301 and star V, in arcsec. This is a measure of the seeing. The 0.9m images on Feb 21 were not in good focus.

Table 2. Calibrated Photometry on 21 February 2004

Star	B	V	R	I
	\pm	\pm	\pm	\pm
IRAS 05436-0007	18.421	16.931	15.704	14.209
	0.085	0.023	0.009	0.006
Comparison Star	16.940	15.648	14.900	14.252
	0.016	0.006	0.004	0.005

Table 3. Spectroscopic Log

Date (UT)	UT	JD	dispersion (Å/pix)	exposure (sec)
2004 Feb 13	02:27	2453048.602	1.1	1800
2004 Feb 23	01:14	2453058.551	1.1	1800
2004 Mar 02	01:31	2453066.564	1.1	3300
2004 Mar 05	01:08	2453069.548	1.1	3600
2004 Mar 08	00:56	2453072.540	1.1	3600
2004 Mar 21	00:01	2453085.500	5.7	3600
2004 Mar 21	23:59	2453086.500	1.1	3900
2004 Apr 06	00:30	2453101.521	1.1	3900
2004 Apr 12	23:28	2453108.478	1.1	3600
2004 Apr 17	23:20	2453113.473	5.7	3300

Table 4. $H\alpha$ Measurements

Date (UT)	$W_\lambda(H\alpha)$	
	emission	absorption
2004 Feb 13	-32	3.3
2004 Feb 23	^a	...
2004 Mar 02	-40	1.8
2004 Mar 05	-46	1.9
2004 Mar 08	-48	<0.6
2004 Mar 21.0	-36	2.0
2004 Mar 21.9	-37	1.5
2004 Apr 06	-30	3.5
2004 Apr 12	-37	1.5
2004 Apr 17	-45	—
mean	-40	1.6

^a $H\alpha$ emission is clearly visible, although no continuum was detected.

Table 5. Ca IR Triplet Measurements

Date (UT)	$W_{\lambda}(8498)$	$W_{\lambda}(8542)$	$W_{\lambda}(8662)$
2004 Mar 21.0	-9.0	-7.9	-4.6
2004 Apr 17	-11.1	-10.4	-7.8
mean	-10.2	-9.4	-6.0











